



Systems Engineering at JPL: Today and Tomorrow

***The Value of System Thinking
Northrop Grumman Workshop***

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March 7, 2017



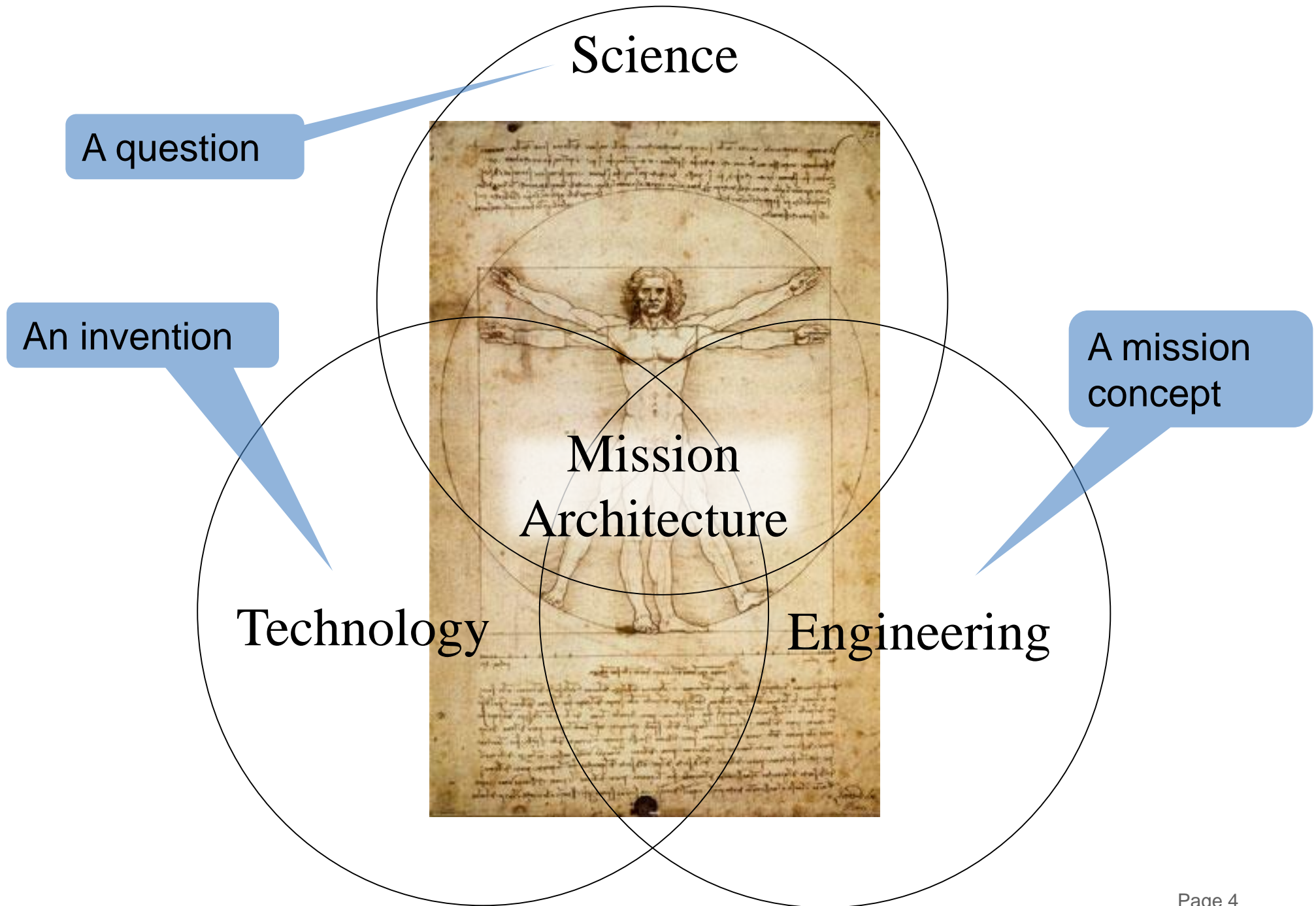
**Jet Propulsion Laboratory
California Institute of Technology**

- **How JPL performs formulation**
- **Key aspect of JPL System Engineering**
- **Expected behaviors of JPL System Engineers**
- **Systems Engineering: The Next Generation at JPL**
- **The Value of System Thinking**

- JPL supports the science community to ideate, mature, and propose concepts for new NASA missions
- JPL continuously “system engineers” requirements and solutions to develop compelling new missions
- The **JPL Innovation Foundry** is our integrated formulation lifecycle enterprise



Every Mission Starts With a Spark

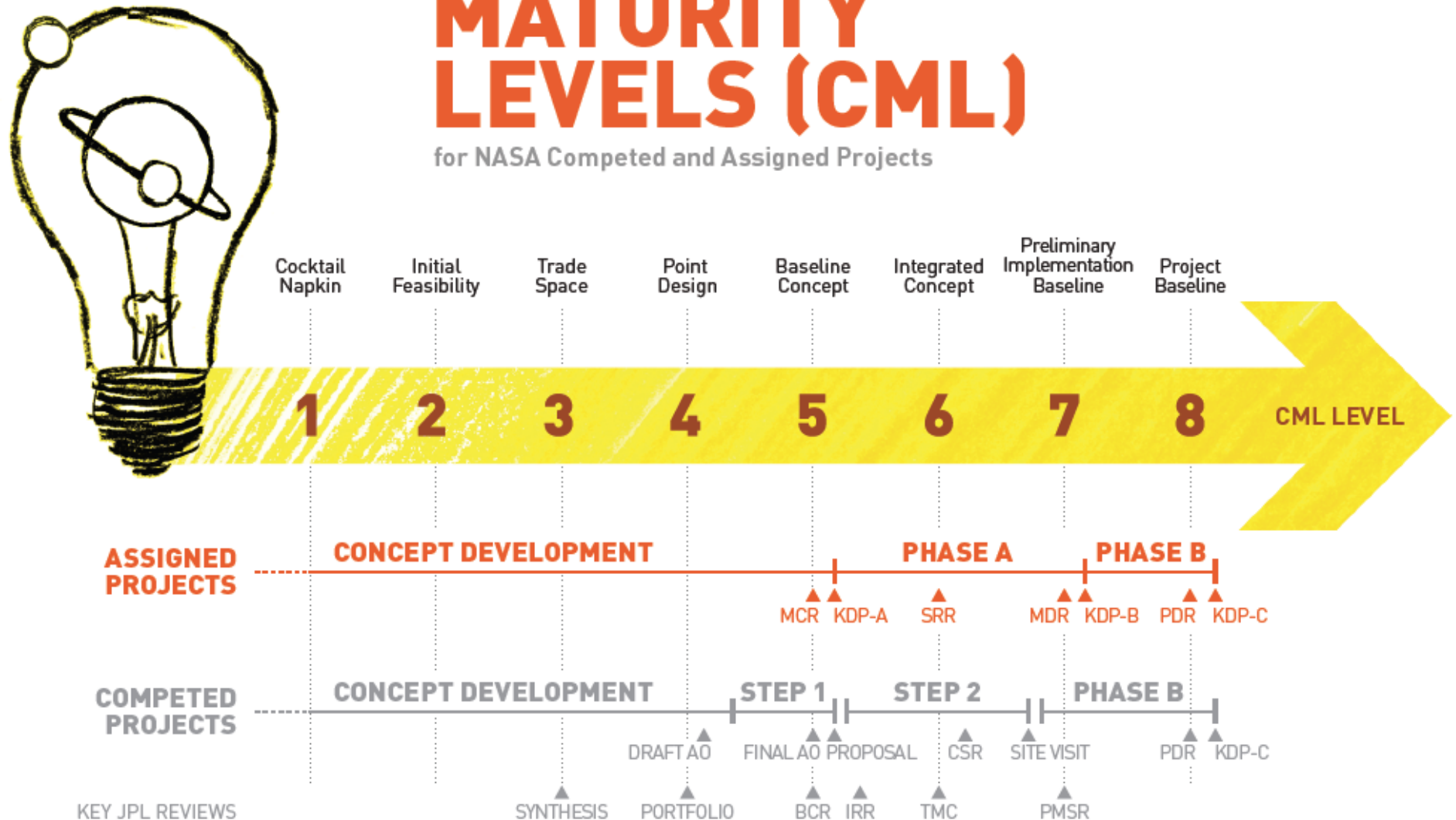


CMLs Correspond to Life Cycle Milestones

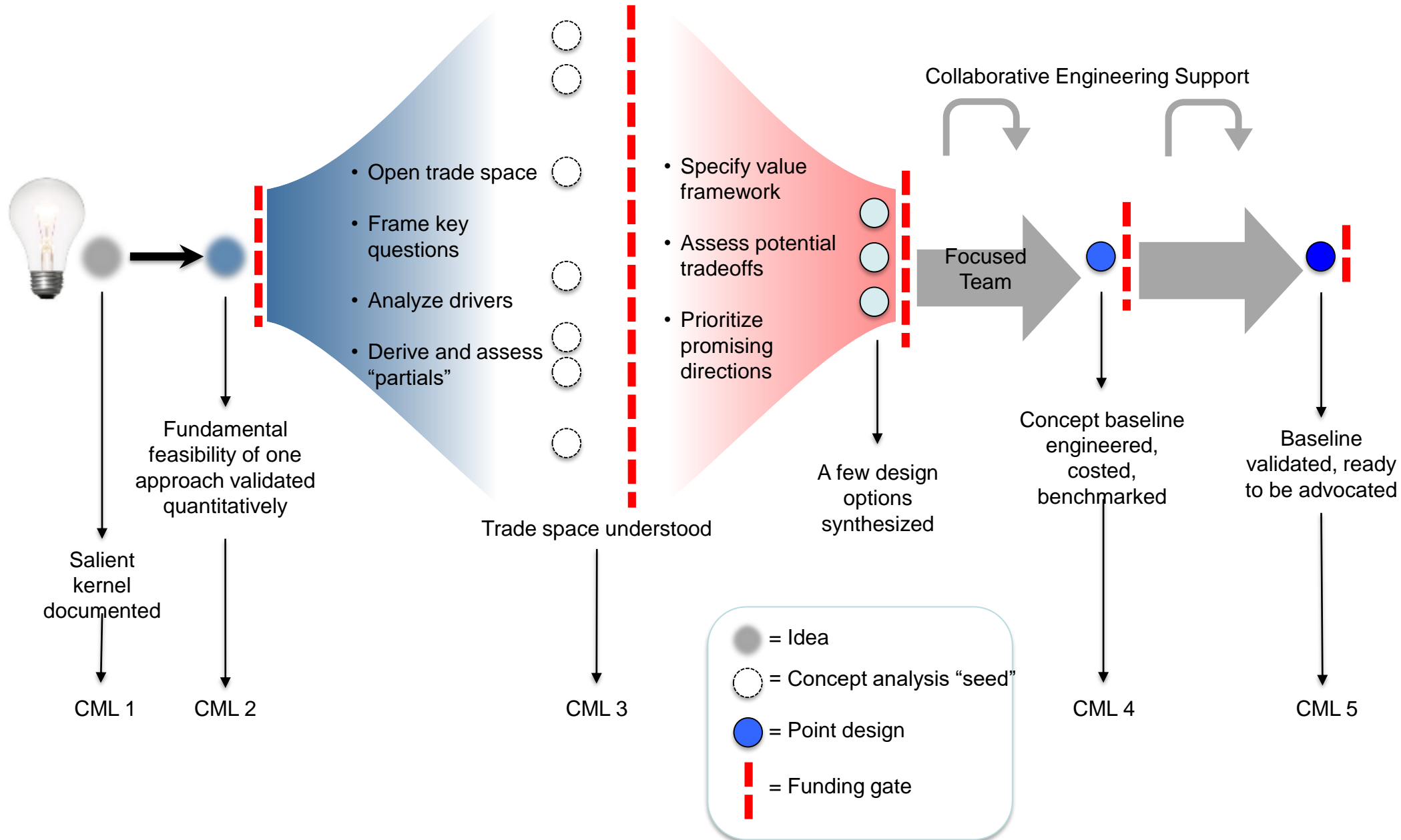


CONCEPT MATURITY LEVELS (CML)

for NASA Competed and Assigned Projects



Evolution of an Idea



The A-Team



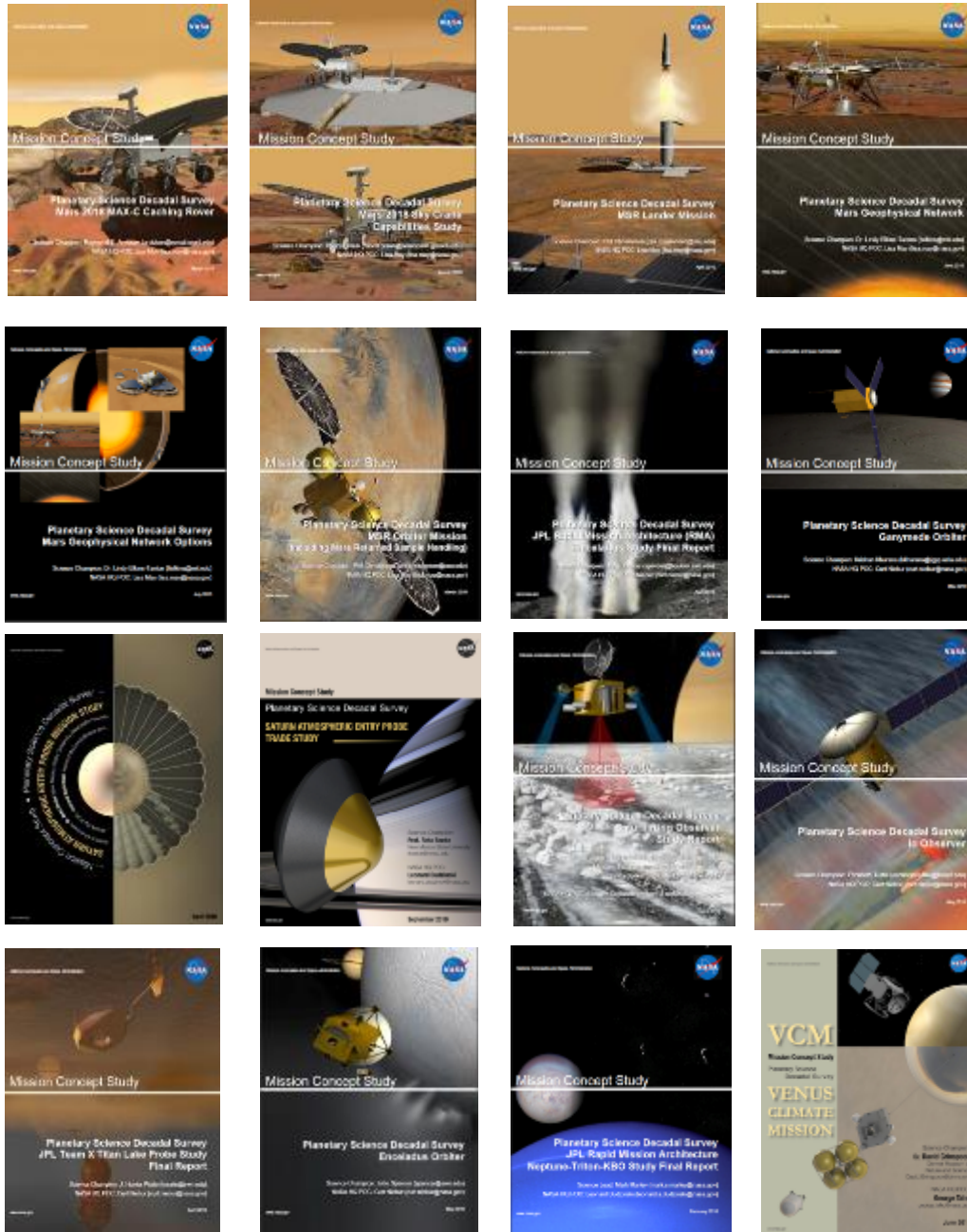
The A-Team efficiently explores the science, implementation, and programmatic trade space in early concept formulation.



A concurrent
engineering team for
rapid design and
analysis of novel space
mission concepts



High Visibility Products for NASA



- Team X supported 16 mission concepts for Planetary Science Decadal Survey
- Team X supported 14 instrument and mission concepts for Astrophysics 2009 Decadal Survey

Key Aspects of SE Today

- Leading the Technical Team through the Life Cycle
- Innovation in Formulation
- The Phase Lead Concept
- Engineering Technical Authority
- Autonomy and Fault Tolerance
- Systems Verification & Validation
 - Test as You Fly
 - The Incompressible Test List
 - Certification of Flight Readiness
- Moving To Operations

Behaviors of a JPL Systems Engineer

- Has Intellectual Curiosity
- Sees The “Big Picture” View
- Sees Connections
- Is Comfortable With Change
- Is Comfortable With Uncertainty
- Has “Proper Paranoia”
- Keeps Track of Resources & Margins
- Has Good Communication Skills
- Has Self-Confidence and Energy
- Has Appreciation For Process

Find The Fault!



National Aeronautics and Space
Administration
Jet Propulsion Laboratory
California Institute of Technology

Systems Engineering: The Next Generation at JPL

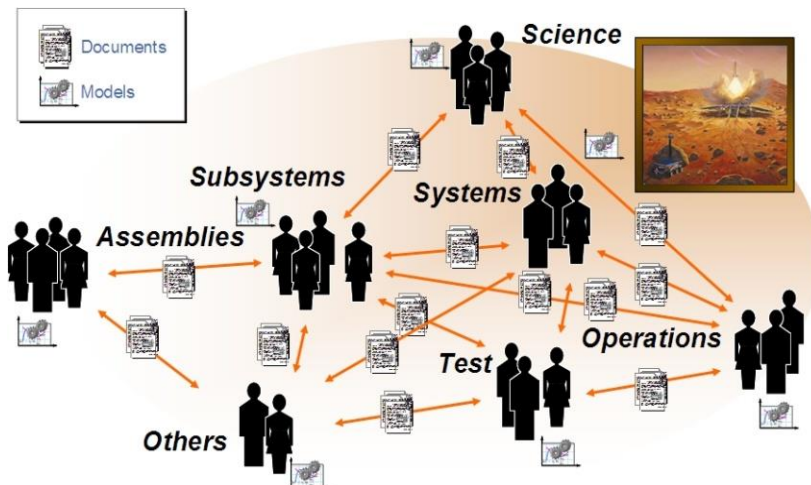
Where Do We Need to Improve our SE?

- Strengthen the quality of formulation products by allowing exploration of a more comprehensive option space and more rapid analysis of alternatives
- Perform early validation of system designs
- Give systems engineers time to do more engineering analysis and less paper management
- Significantly improve the quality of communications and understanding among system and subsystem engineers
- Achieve greater design reuse
- Align with the expectations and work habits of the next generation of engineering talent
 - this is the way new engineers are being trained and the way many of our early career engineers want to work

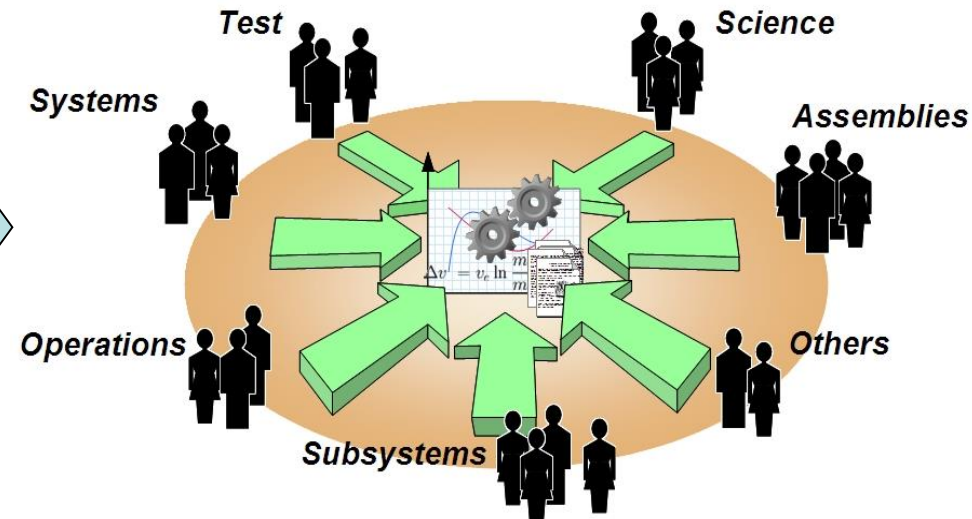
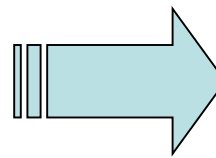
But the bottom line is to...

- Reduce the number of product and mission defects in the face of growing complexity
- And increase productivity/reduce costs

- **Integrated Model Centric Engineering (IMCE)** is a JPL initiative established to accelerate the application of model-centric engineering (centered around MBSE) at various levels of detail across the full system life cycle, with a focus on:
 - developing **an institutional re-usable capability** for model-centric engineering practices
 - **nurturing model-centric engineering** practices by partnering with doing organizations and projects



Today: Standalone models are related through documents

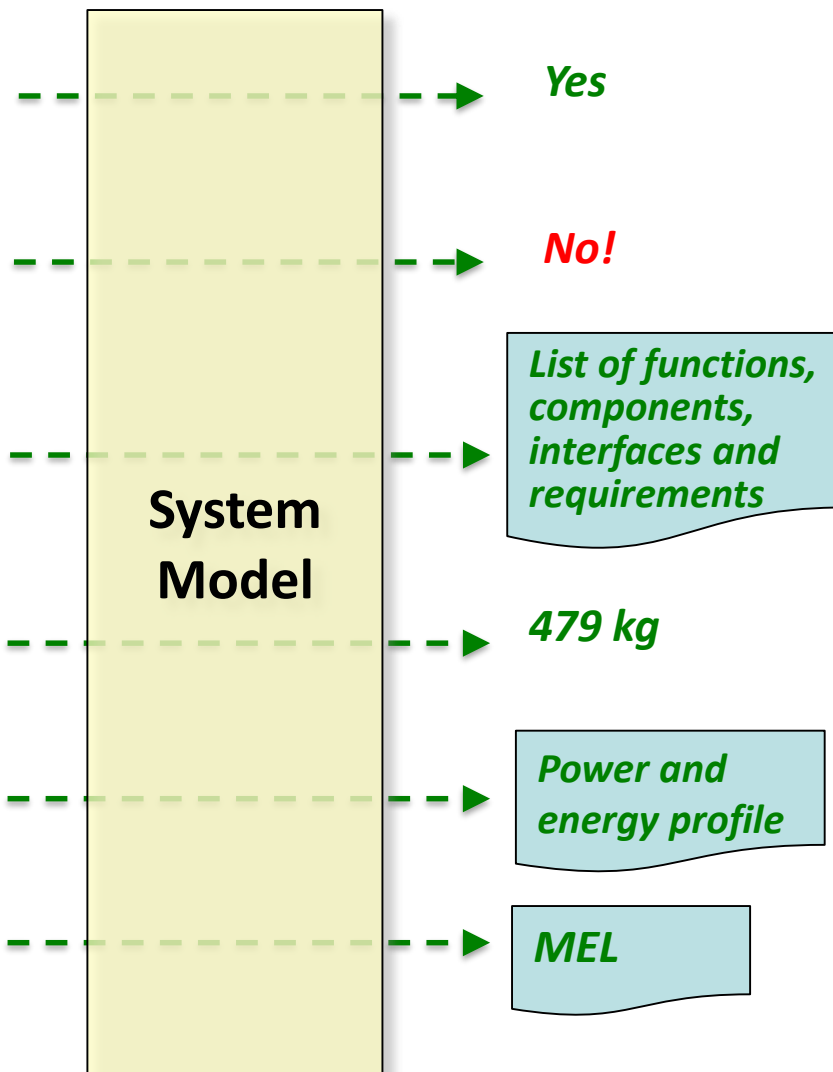


Future: A shared system model with multiple views, connected to discipline models

The Concept of the System Model is Fundamental

A well-structured system model can be analyzed to answer a variety of questions

- Does every component trace to a requirement?
- Have both sides of every interface been specified?
- If this requirement changes, what is potentially affected?
- What is the dry mass of the flight system?
- Show power and energy used for mission scenario x
- What is the mass rollup?



Using traditional methods:

Manual mapping from every powerpoint block diagram to DOORS.

Manual mapping from every powerpoint block diagram to every ICD.

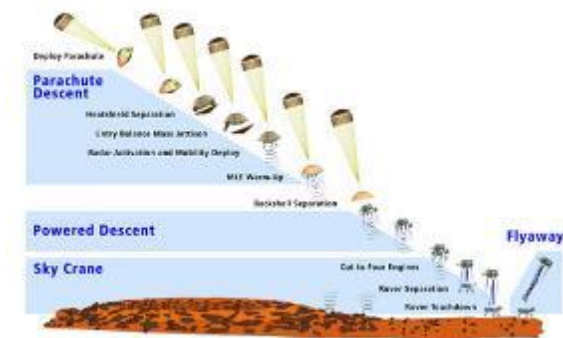
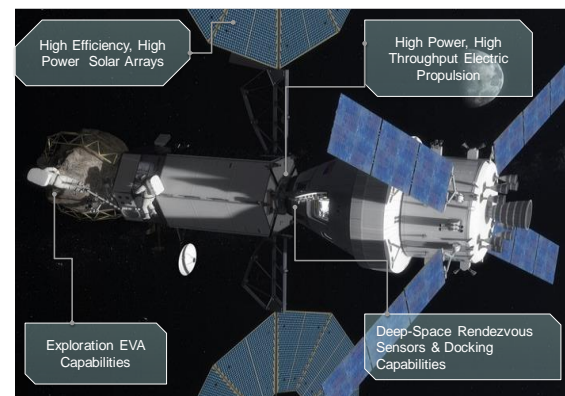
DOORS trace gives only a clue; critical info is in SE's head.

Manual update of Excel file MEL + manual consistency check of equipment list against all powerpoint block diagrams.

Manual update of Excel file PEL + manual consistency check of equipment list against all powerpoint block diagrams.

Same as 'dry mass' above.

- **Asteroid Redirect Robotic Mission (ARRM) Phase A**



Europa Clipper - Challenges During Formulation Phase

- **Managing multiple architectural alternatives**
- **Reliably determining whether design concepts “close” on key technical resources**
- **Ensuring correctness and consistency of multiple, disconnected engineering reports**
- **Managing design changes before a full design exists**

Europa System Model Framework

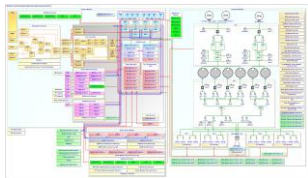
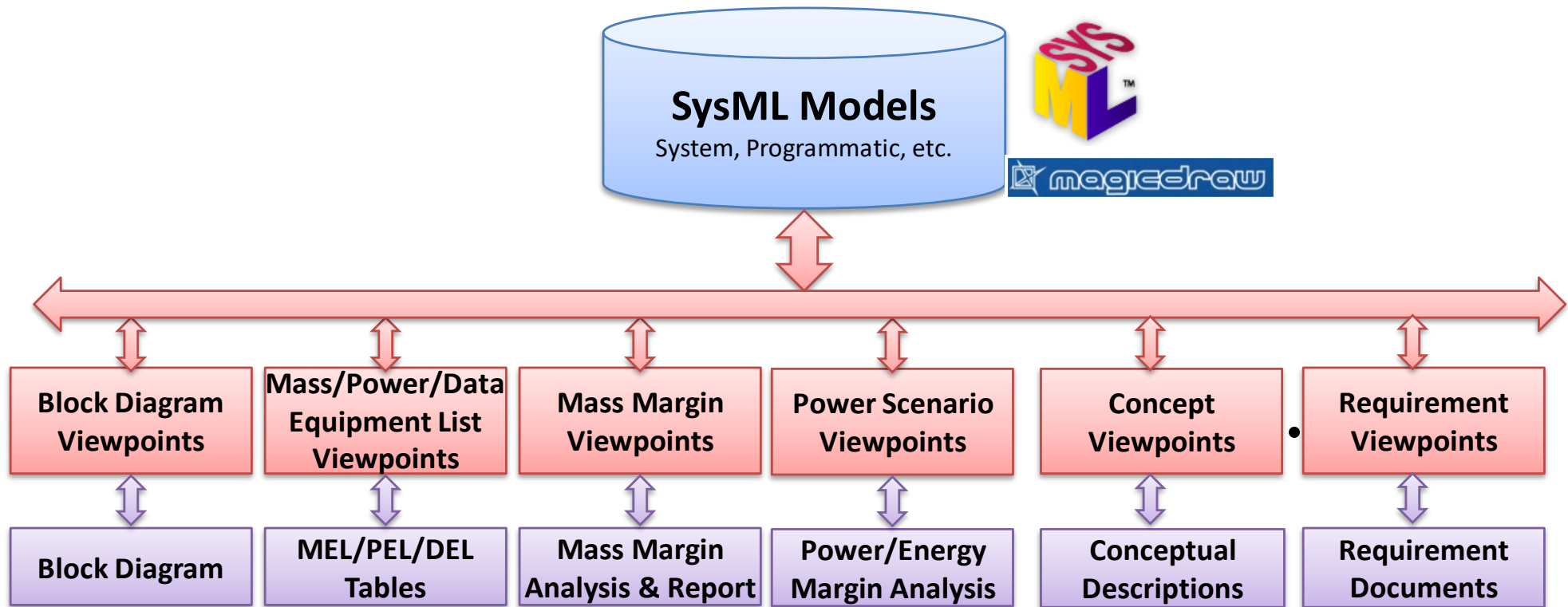


Table 2.1. MEL/PEL/DEL Tables for Europa

Block	Category	Table of Contents	Mass (kg)	Power (W)	Thermal (W)	Thermal (K)	Thermal (C)	Thermal (F)	Thermal (R)
1	Block	Table of Contents	1	1	1	1	1	1	1
2	Block	Table of Contents	2	2	2	2	2	2	2
3	Block	Table of Contents	3	3	3	3	3	3	3
4	Block	Table of Contents	4	4	4	4	4	4	4
5	Block	Table of Contents	5	5	5	5	5	5	5
6	Block	Table of Contents	6	6	6	6	6	6	6
7	Block	Table of Contents	7	7	7	7	7	7	7
8	Block	Table of Contents	8	8	8	8	8	8	8
9	Block	Table of Contents	9	9	9	9	9	9	9
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98	Block	Table of Contents	98	98	98	98	98	98	98
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100	Block	Table of Contents	100	100	100	100	100	100	100

ASRG Clipper Mass Margin					
Launch		LAUNCH			
Total Mass (kg)		Flight System Mass kg			
		CBE	CRF	MTV	
ASRG Clipper					
Acoustic Mass Spectrometer		28	50%	42	
Ion Propulsion: Raster		13	50%	25	
Ion Propulsion: Thrusters		2	50%	4	
Communication: Imager		2	50%	4	
Communication: Antenna		2	50%	4	
Fast Langmuir Probe (Inboard)		1	50%	2	
Fast Langmuir Probe (Outboard)		1	50%	2	
Thermal: Mass		8	50%	3	
Proposed		70	50%	105	
ASRG		88	24%	122	
Power		172	43%	248	
Thermal		22	50%	33	
Electronics		100	25%	150	
Communication: Structures		100	25%	150	
Thermal: Controller		88	30%	132	
Thermal: Radiator		100	25%	150	
Electronics		72	30%	108	
Thermal: Radiator		8	30%	12	
Active Resistor		150	30%	225	
ASRG		150	30%	225	
Flight System Mass		242	30%	363	Mass Prop
ASRG		242	30%	363	MTV
VIS: Magnetometer		0	0%	0	
VIS: Camera		40	40%	80	
Propellant		6	0%	0	
Thermal and Wiring		0	0%	0	
ASRG		100	100%	100	100%
Flight System Total Mass		342	100%	500	
ASRG		342	100%	500	
USC/University of Michigan - ASRG					
After 1/1/01					
System Margins					

Europa Clipper: Benefits Realized Through MBSE

- **Communication of technical information** within project and among disciplines is more efficient and accurate
 - Not limited by foreseeable levels of increasing system complexity
 - Easily integrated with existing discipline tools (MBSE is the *keystone* for full Model Based Engineering)
- **Re-use and evolution of alternate system design elements**
 - 3 full mission studies in the time it usually takes for 1 or 2
 - 5 parallel configurations maintained
- **Improved control over the evolution of system designs**
- **Consistent, rapid generation of technical margins** and normalization of risk assessment
 - Identical automated analyses are applied to all configurations and versions
- **Efficient generation of project documentation**
 - Ensuring consistency of documentation by drawing from same system model
- **Bridges from college education** to project best practices
 - Recent graduates are arriving with knowledge of and expectation of using MBSE methods

Mars 2020 is not a typical project for JPL

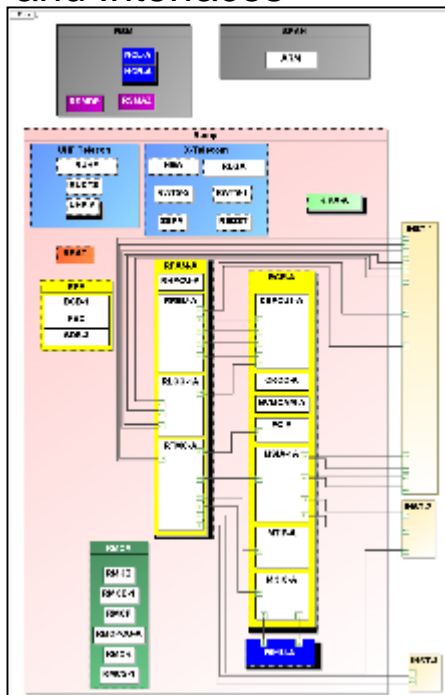
- Much of the H/W and S/W design is reused from MSL
- However, new mission, science objectives, and instruments
- Highly cost-constrained
- Leverage heritage via “build-to-print” philosophy

Needed to modify the SE approach to address experiences on the MSL project

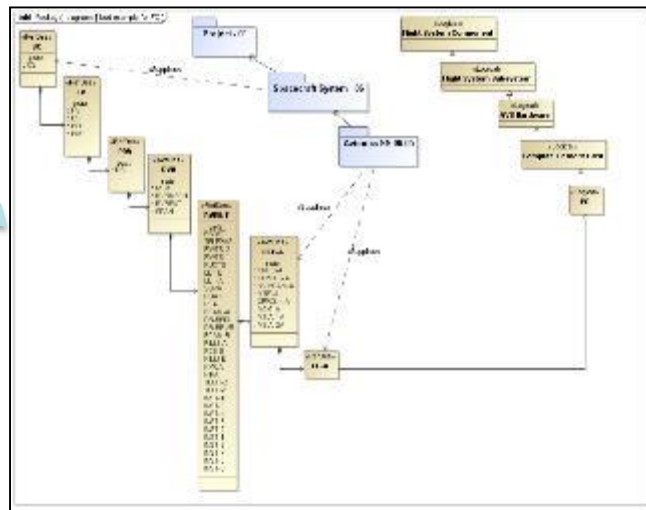
- Keep SE products updated with the ongoing design/developments/tests
- Sharing information across a diverse team avoiding information “silos”
- Improving the flow and traceability of design decisions and tests
- Managing cross-cutting complexity and understanding of scope
- Preempting the V&V “armageddon” at the end of the project – 3 test beds running 7 days a week
- Improving parameter tracking and test correspondence (and visibility by others on this)

Example System Modeling Products

System Block Diagrams and Interfaces

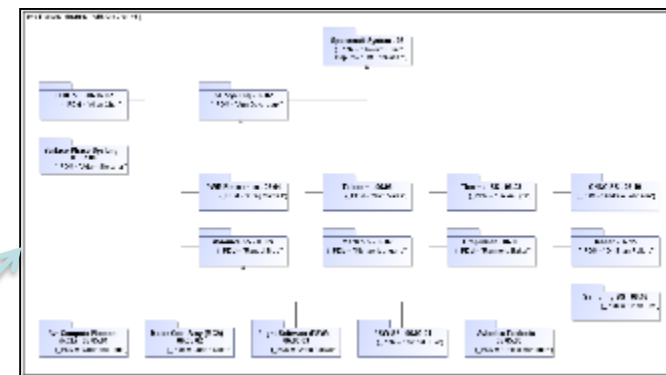


Physical Decomposition, Logical Decomposition, and WBS



Linking information to core components (Reference Designators)

Org Chart

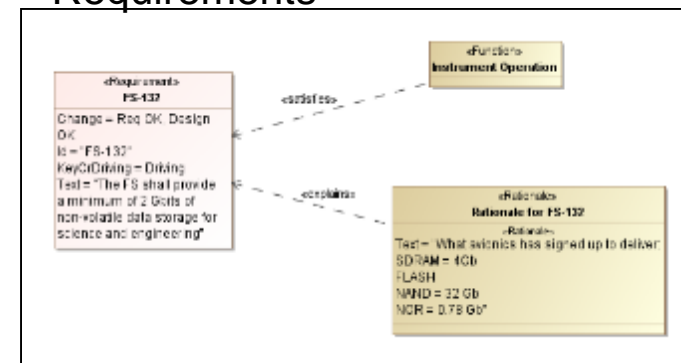


Resource Tracking (e.g., subset of web-accessible MEL)

Flight System	Flight Quantity	CBE (kg)	MEV (kg)	Contingency (Percent)	Contingency Level	CBE All Count (kg)	MEV All Count (kg)
Flight System	1	915.06	942.27	2.97	N/A	915.06	942.27
RPS	1	44.79	45.63	2.00	N/A	44.79	45.63
RTG	1	44.79	45.63	2.00	N/A	44.79	45.63
PAYLOAD	1	72.25	73.73	2.04	N/A	72.25	73.73
Thermal	1	41.14	41.96	2.00	N/A	41.14	41.96
SVRTSTAT	12	0.01	0.01	2.00	N/A	0.16	0.16
RIPA	1	14.58	14.87	2.00	N/A	14.58	14.87
SVRTHRM	1	17.28	17.63	2.00	N/A	17.28	17.63
CHRSFL	1	0.90	0.91	2.00	N/A	0.90	0.91
SVRPRF	192	0.00	0.00	2.00	N/A	0.28	0.29

Subset of patterns are extended from institutionally-and Europa derived patterns

Assessment of Key & Driving Requirements



System model provides integrated, consistent, and broadly-accessible design information and change assessment

The team has seen value, particularly in generating artifacts like the MEL, heritage tables, and interface block diagrams and making them broadly accessible to the team

- Providing **mutually-consistent products** that are readily updated (e.g., a change to an item in one place immediately propagates that update to all affected views/products).
- Going through this process is also helping **to identify areas of inconsistencies** in separately generated and maintained historical documents, spreadsheets, etc. inherited from MSL. Getting these into the model is helping us to **reconcile these discrepancies**.
- Products are being created that are **quickly and broadly accessible** (e.g., via web interface) by the wider team (e.g., not having to track down the latest version of an Excel spreadsheet on an individual's computer).
- This is also helping **with increasing the visibility and understanding of the design** by the team.

“The model help us with knowledge transfer and continuity as personnel come in and out of the project over the coming years.”

ARRM Unique Challenges

- **Multi Center Team**

- Many more organizations than normal (JPL, JSC, GRC, KSC, LaRC, GSFC, Contractor) and working for two HQ Directorates: Human Exploration and Ops (HEOMD) and Space Technology (STMD)
- Much more fully integrated into the team (the PSE team has substantial core roles performed by people at other NASA centers)

- **Technology Demonstration on a Large Scale**

- High power arrays (>50kW) and ion thrusters with commercial possibilities
- Asteroid and astronaut proximity operations

- **Many New Operational Modes**

- Picking up a boulder
- Planetary defense
- Exploration robotic spacecraft docking to a manned spacecraft

- **Out of Sync Project Elements**

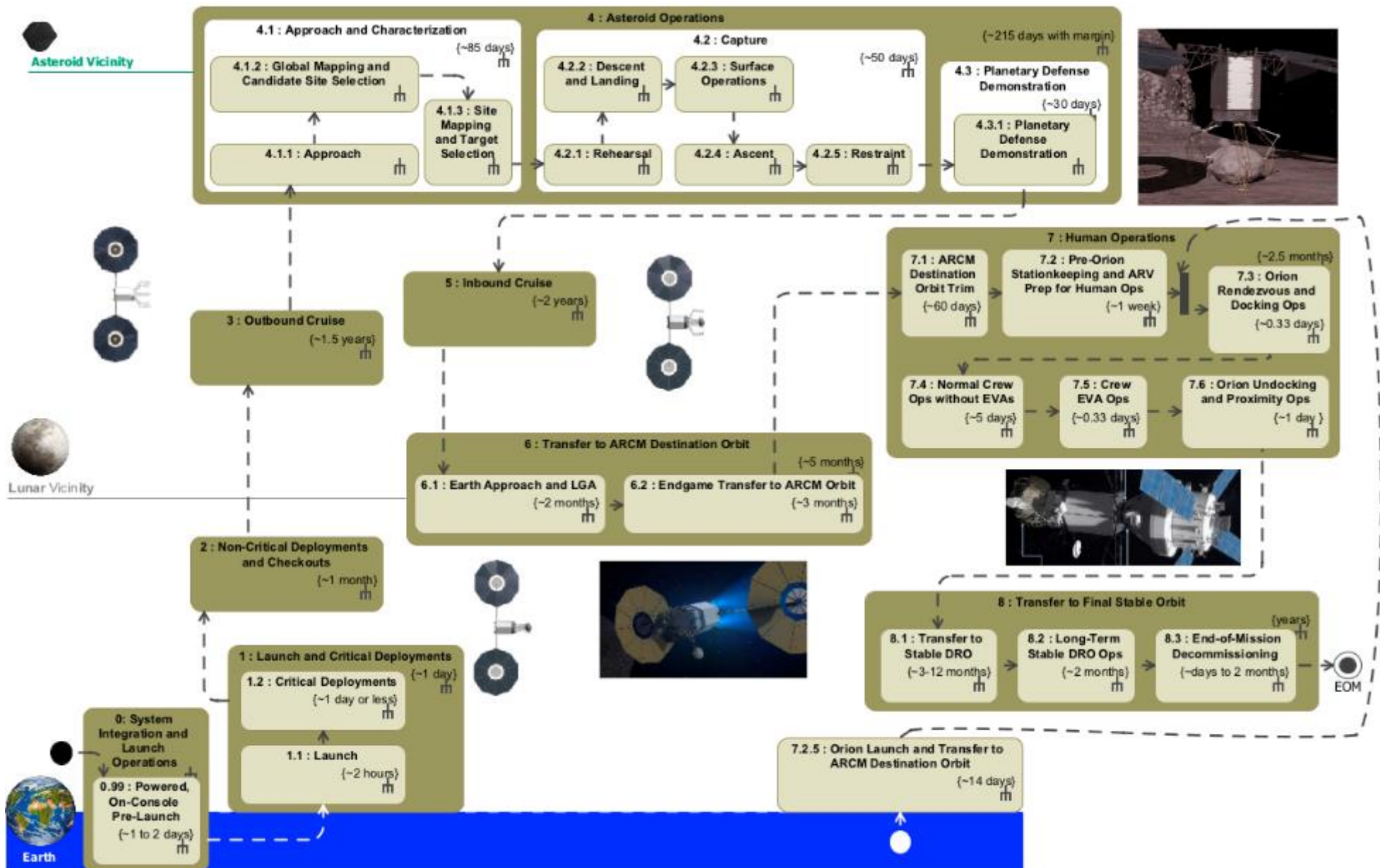
- Late start of spacecraft contractor due to funding constraints
- Human mission does not launch until well after we do



ARRM - What we want to accomplish with MBSE

- **Strive for “Single Source of Truth” database primarily covering the following areas, and the relationships between them:**
 - Requirements
 - Functional architecture and Concept of Operations
 - Verification and Validation
 - Other (Product Technical Structure, OBS, Personnel & Roles, Document List, Nomenclature)
- **Enable collaborative development and maintenance by multiple centers and contractors**
 - By systems engineering, discipline engineering, and project management teams alike
- **Generate a variety of stakeholder deliverables and viewpoints that are consistent with all other generated content**
 - Support different perspectives and needs from the same underlying data
- **Facilitate sharing of the “Single Source of Truth” with other tools and across firewalls through use of GovCloud**
- **Brian Muirhead – ARRM Project Manager:** “MBSE is an essential element of the Project’s implementation and it’s working in our planned implementation and at the level we need. Will continue to look for opportunities to take advantage of future capabilities.”


Mission Operational Concept Definition

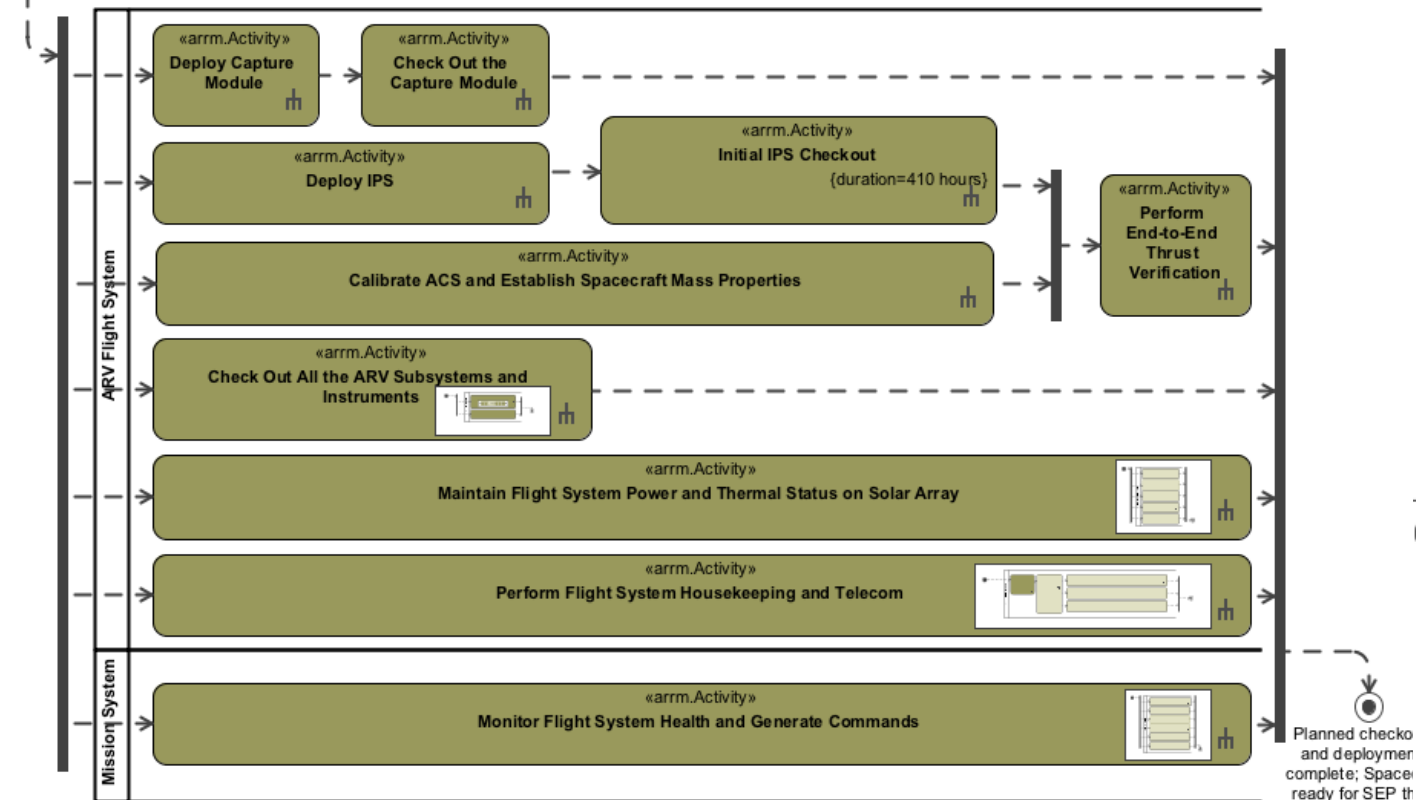


Mission Operational Concept Decomposition

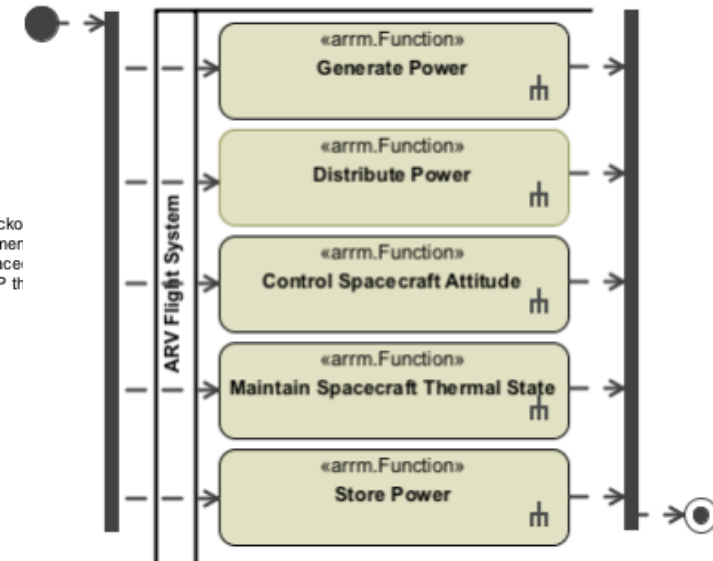
mission decomposition: phases (--> sub-phases) --> activities --> functions

[Non-Critical Deployments and Checkouts]

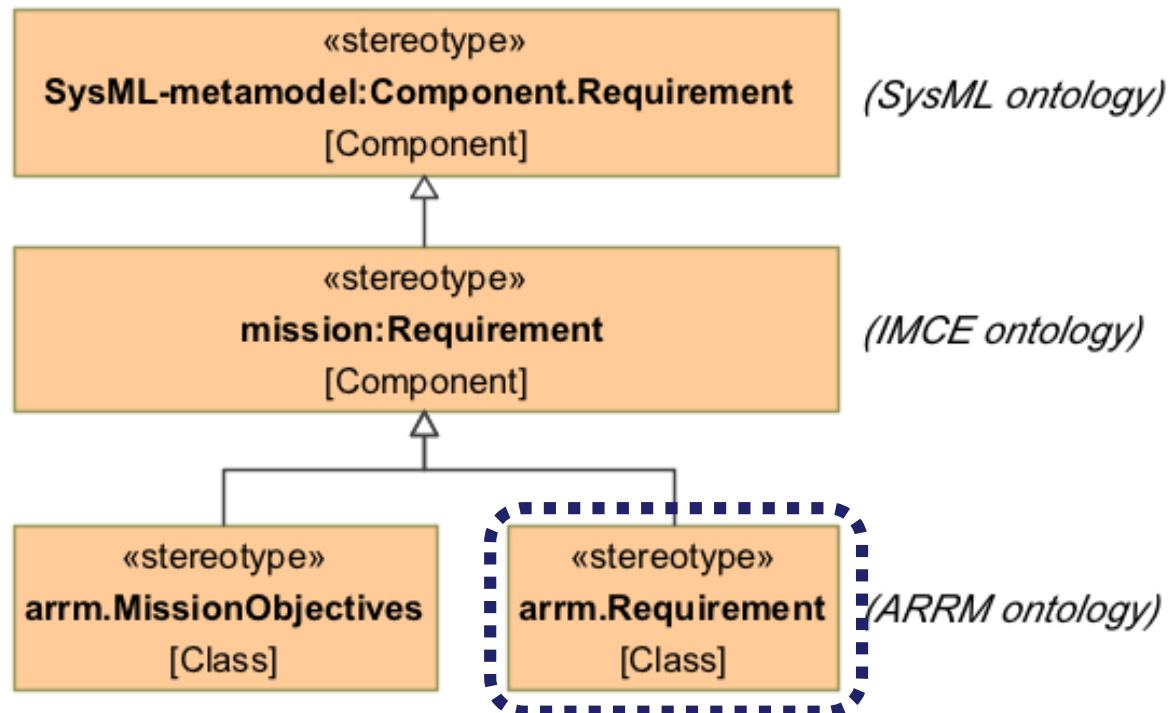
 solar arrays deployed & in 3-axis stabilized communications



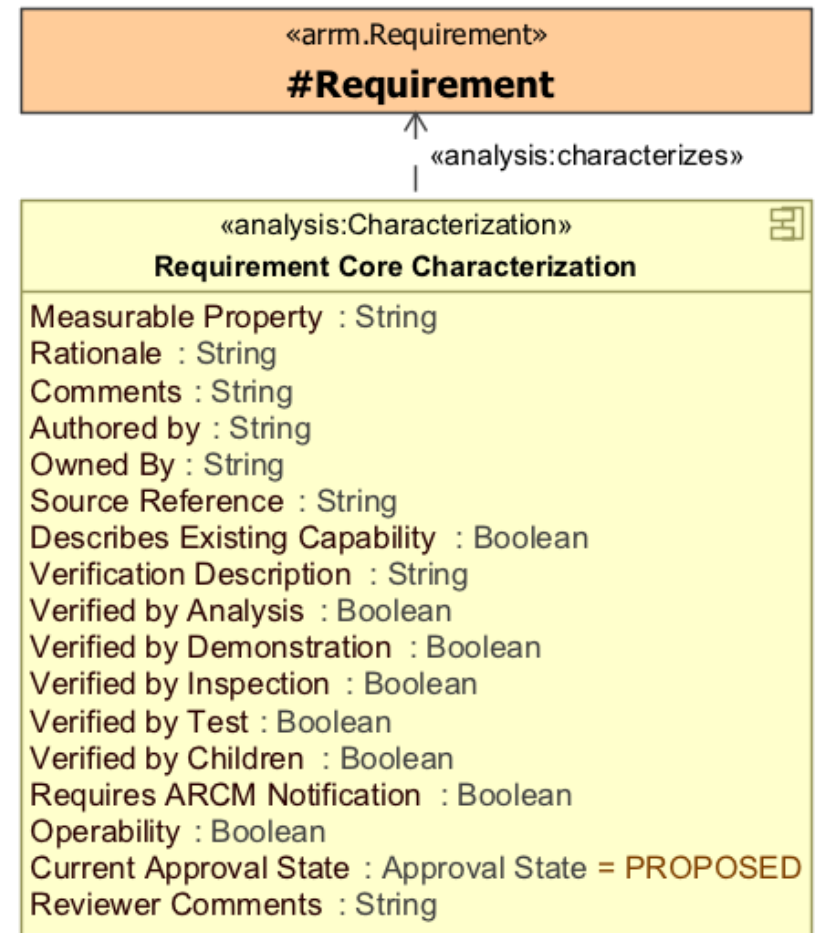
[Maintain Flight System Power and Thermal Status on Solar Array]



Requirements Development



characterization for quantitative and/or **qualitative** analysis



- **It Enhances Communication**
- **It Improves Productivity**
- **It Improves Quality**
- **It Supports Integration**
- **It Helps Manage Complexity**
- **It Enables Reuse of Institutional Knowledge**
- **It Attracts Early Career Talent**

NASA/JPL MBSE Workshop and Symposium - January 2017

NASA

- HQ
- AFRC
- ARC
- GRC
- GSFC
- JPL
- JSC
- KSC
- LaRC
- MSFC
- SSC

Industry

- BAE Systems
- Boeing
- Booz Allen
- Ford Motor
- General Motors
- Lockheed Martin
- Northrop Grumman
- Orbital
- Raytheon

International

- Airbus
- ESA
- ESO
- GMTO
- JAXA
- Thales

Other

- APL
- Aerospace Corp
- Draper Labs
- INCOSE
- NSF
- MITRE

Academia

- Caltech
- Florida Inst Tech
- Georgia Tech
- McGill U.
- MIT
- Purdue U.
- Stevens Inst.

Defense

- DoD
- Army/ARDEC
- Navy/NAVAIR
- USAF

Vendors

- Intercax
- NoMagic
- Phoenix Model Center
- Siemens
- Vitech

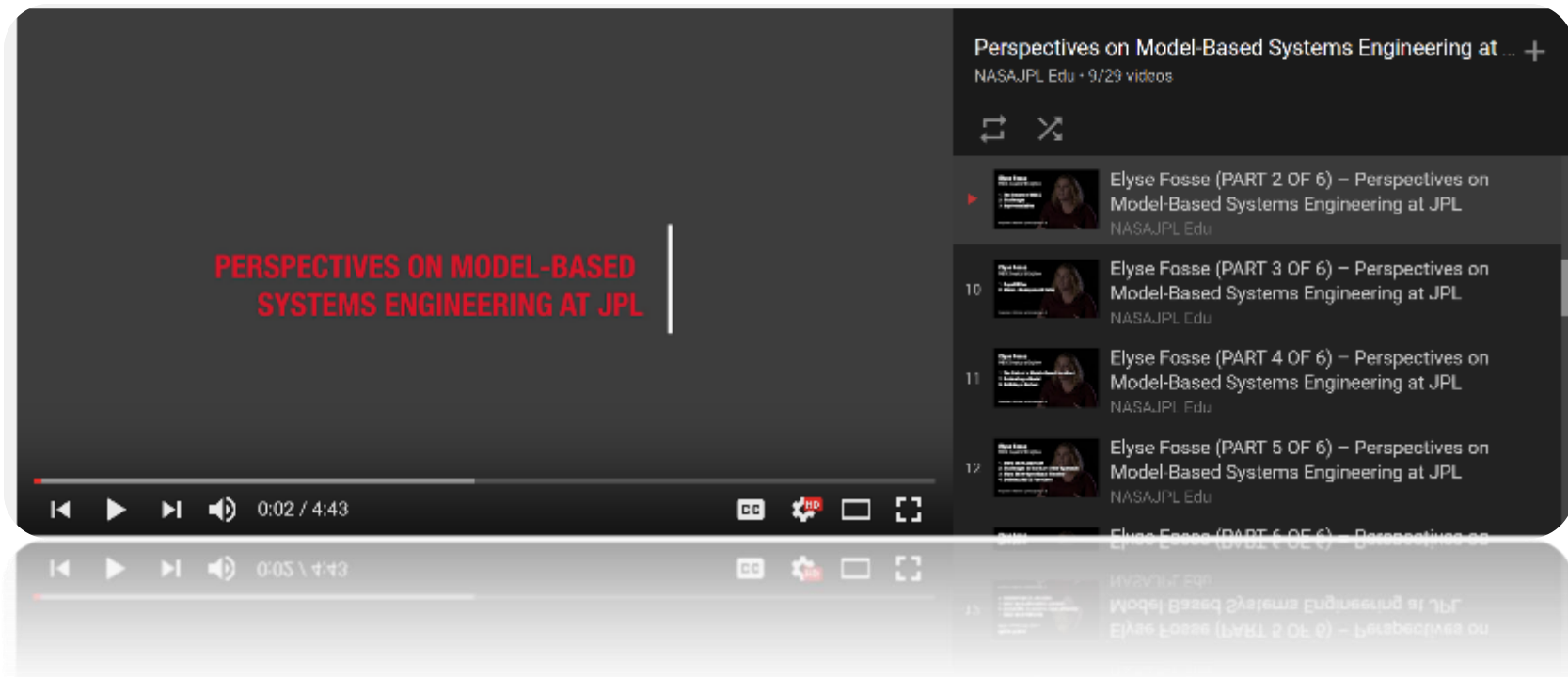
* Not an exhaustive list

MBSE Videos on YouTube

We have developed a series of videos with JPL practitioners talking about their experiences with MBSE which are available on YouTube.

Check it out at

<https://www.youtube.com/playlist?list=PL9TFrgFq7556gaaeRwCYCz1CqjEvWGl8Y>.





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Administration
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The Value of System Thinking



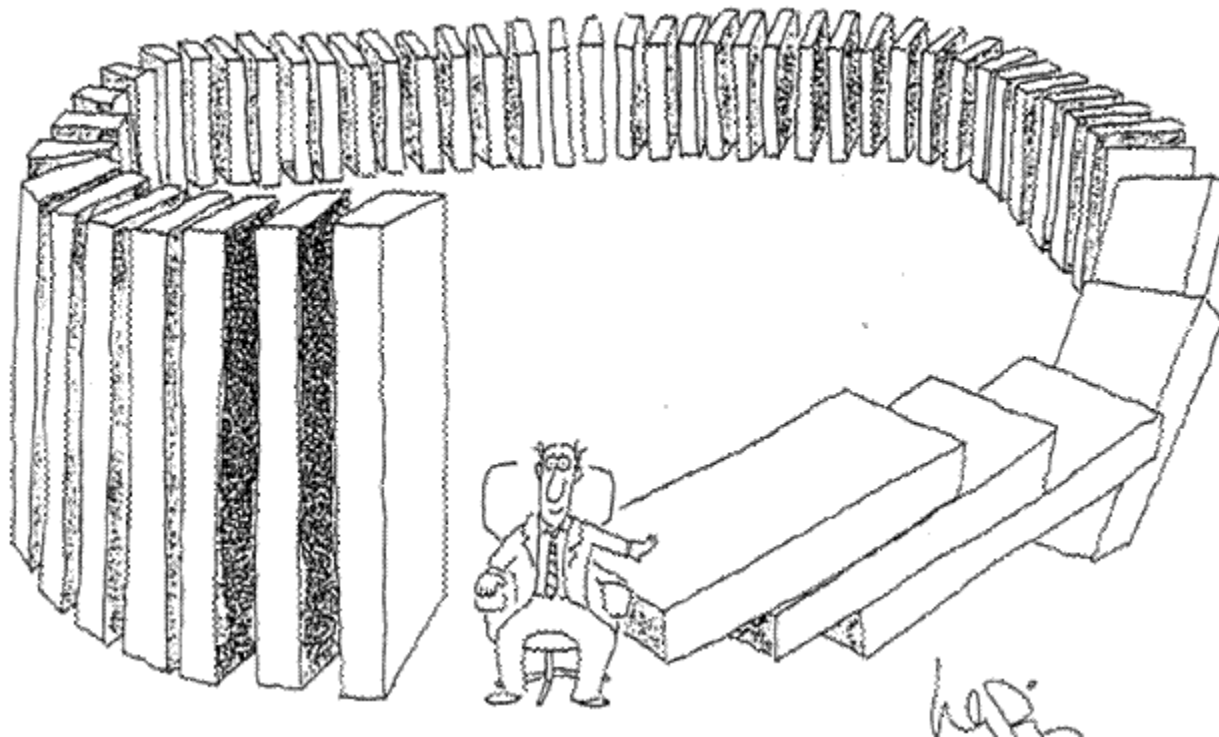


System Thinking is:

- Not limited to the system engineers
- A commitment to understanding one's position or task within the context of the whole
- Understanding beyond the prescribe requirements
- Knowing how the information or product one produces will be used
- Seeking understanding of the unexplained or puzzling
- Thinking beyond the moment
- Prevalent throughout the organization

Value System Thinking

- Improves communications
- Creates better understanding
- Improves the quality of the final product
- Helps prevent/mitigate mistakes



....Thank You!